SOLAR ARRAY PERFORMANCE FOR MARS ENVIRONMENTAL SURVEY MISSION (MESUR)

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ABSTRACT

The Mars Environmental Survey Mission (MESUR) is a low cost, near term mission to study: chemical composition of the martian surface; structure and circulation of the martian atmosphere; and structure and dynamics of the martian interior. To meet the science objectives of the mission, a network of 16 landers will be placed at various latitudes and longitudes on Mars. These 16 Net-work landers will be preceded by an engineering Pathfinder mission which will demonstrate entry, descent and landing as well as some of the engineering subsystems. This paper discusses mission concept, spacecraft- system design, power system requirements, and the solar array power system for Pathfinder.

THE MESUR MISSIONS

The study of the surface of Mars in 1977-1979 by the two Viking landers provided a lot of information about Mars but also raised many questions. To start answering these questions, scientific measurement-s that can be achieved from orbit will be made by the Mars Observer mission which launched in September 1992. The next step requires returning to the surface to acquire data from many different sites simultaneously. MESUR Net work will place up to 16 landers at various sites which allows science investigations of globally distributed phenomena such as seismic activity and weather. MESUR Network data and communication needs will be enhanced by use of a Mars orbiter.

Some of the Network landers may carry and release a Microrover. The Microrover would enable high resolution scientific studies such as imaging and spectroscopy at geologically interesting sites out-side of the lander's reach or 'cont-amination zone.

The other significant. attribute of t-he MESUR missions is the limit that has been placed on the overall and annual costs. MESUR Pathfinder must be designed and built for no more than 150 million dollars. The entire network of landers has to be developed and built for one billion dollars at no more than 150 million dollars per year. This is in contrast- to the Viking program that cost 3.5 billion in today's dollars. The limit in cost has consequences for all of the subsystems and may determine the technology options.

The Pathfinder mission that precedes the Network mission is designed to demonstrate the entry, descent, landing, and some of the engineering subsystems. In the case of the power system, the Pathfinder will demonstrate the performance of solar arrays in the martian thermal and atmospheric environment. as well as operation of the various power elect-ronjcs components.

MISSION OVERVIEW AND SPACECRAFT DESIGN

MESUR Pathfinder must be launched in 1996 in order to provide engineering data for the 16 Network landers. Pathfinder will use a new landing method instead of a fully controlled landing to reduce cost and complexity. Other new, low cost. systems will be used in the power system and in thermal control . Successful demonstration of these new systems is the most important goal of the Pathfinder lander. The Pathfinder lander will also carry the first Microrover. The Microrover will carry at least one science experiment, which will be used during the one week to thirty day Pathfinder mission.

The MESUR Network mission will globally distribute its set of landers over a period of years through a series of launch opportunities thereby minimizing t-he annual resource requirements. The landers will be made as similar as possible to reduce cost . The mission scenario is to build up the global network over three launch opportunities using five Delta class expendable launch vehicles (ELVs) . Four of the ELVs will launch 16 probes while the remaining ELV will launch a communication orbiter. The first launch will occur in 1999 and will send four landers. After a 12 month journey these landers will have to maintain a direct communication link to the Earth until 2002 when two launches will have delivered another four landers and the communication orbiter. The reason for delaying the communicat-ion orbiter is to keep the spending profile flat. The final eight landers will arrive two years later. The network will be designed to operate for one martian year after the last landers arrive or until 2006.

The landers are part of a probe which consists of a bioshield, cruise stage, aeroshell, parachute, and lander. Shortly after launch, t-he bioshields are opened and the cruise stages are released. Figure 1 shows the cruise configuration of Pathfinder. The space craft are spin stabilized during cruise and initial entry and are three axis stabilized during the final descent . The landers are separated from the cruise stage just prior to Mars atmosphere. c entry. The lander and aeroshell enter the atmosphere rotating. The aeroshell heat, shield will then be jettisoned and thrusters fired to despin the lander.

As mentioned earlier, the engineering objective of the Pathfinder is to demonstrate t-he cruise, entry, descent-, and landingsystems that will be used by Network. Pathfinder will also provide inheritance for flight, mission, and operational systems. The Pathfinder spacecraft aeroshell will be oriented for a 20 degree entry angle and an ablative heat shield protects the lander from the aerodynamic heating. A parachute is deployed at about 11 km altitude to reduce descent velocity. At about- 8 km altitude t-he heat shield is released and at about 3 km the lander is released on a 100 m tether to reduce the possibility of the parachute covering the lander after landing. At about 2 km above the ground the air bags are deployed around the lander. The air bags are on all four faces of the tetrahedral shaped lander and will absorb the landing loads in all directions and attitudes. The parachute is released right after lander touchdown and the lander is allowed to come to rest. At this time the air bags are deflated and the petals of the lander are deployed - righting the lander. The Pathfinder will collect data on system performance during cruise, entry and descent, . Data on the atmosphere will also be collected and some will be returned prior to impact. . The rest of the atmosphere c data will be returned after petal deployment. Figure 2 shows the landed configuration of Pathfinder.

The trip time to Mars is about one year and Pathfinder will be designed for one month of operation on the surface. The aeroshell diameter is 1.65 m and the height of the cruise stage is 1.5 m. Each petal of the lander is 1.13 m2. The mass of the spacecraft at cruise is 400 kg and the lander mass is about. 200 kg.

PATHFINDER POWER SYSTEM OPTIONS

Preliminary power requirement estimates are made prior to detail design and therefore typically have a large margin (30% in this case) . Pathfinder and the early Network landers must communicate directly to Earth since there will be no orbiter in place. This communication requirement along with other lander needs such as instrumentation, computation, and heating results in an estimate of 1464 watt-hours of energy. The exact power requirements for many system components are still being defined.

The power source options for MESUR include a radioisotope thermoelectric generator (RTG) , a solar array, and primary batteries for very short. mission life or microrovers. There are several factors that must be considered in deciding the final power system for each part of the MESUR mission. An RTG is very expensive and has a long delay period due to multiple approval requirements. These fact, ors rule out. an RTG for Pathfinder. Batteries are heavy and do not. operate well when they are cold. Choice of a primary battery Pathfinder power supply would restrict the mission life to only a few days which is too short a time. Thus Pathfinder has solar arrays and high energy density secondary batteries for its baseline power system.

The Network landers may be located at, extreme latitudes or the poles. The mission scenario calls for the first Network landers to operate for seven years to complete the nominal mission objectives. During the seven years, the power system will go through day/night light and temperature cycles, as well as the seasonal variations in light and temperature. Seasonal dust storms of varying intensity and duration can be expected and the power system must be able to survive and operate during these storms . These considerations may mean the early Network power system would be RTGs .

The Pathfinder baseline power

system consist, s of a cruise solar array, a lander solar array, and a shared peak power tracker (PPT), secondary battery, power distribution unit (PDU), and pyro switching assembly (PSA) . Figure 3 is a block diagram of the power system. The solar array output is connected t-o the PPT which is a buck switching type regulator. The PPT sets the solar array operating voltage at the maximum power point during peak loads and varies the current based on the battery's state of charge. The PPT output is tied directly to t-he battery.

Two AgZn batteries are planned ant] will each have 18 fifty ampere-hour cells. The PDU consists of]at.thing relays and distributes the power to various loads on the spacecraft.. l'he PSA provides the energy storage, switches, and firing circuits for all of the pyro events during the mission.

The baseline Pathfinder" mission is to land in the mid-latitudes at an areocentric longitude of 212 degrees. Since the convention places the areocentric longitude 0 at northern latitude vernal equinox, the landing time is halfway through t-he southern spring. As will be discussed later t-his landing time presents some design risk however is also present the best, compromise of cost, and Earth communication. Because of greater design uncertainty, the most studied part of the Pathfinder power system to date is the lander solar array.

LANDER SOLAR ARRAY

Mars atmospheric models have recent] y been published by Landis and Applebaum [1], and Haberle, et. al. [3] and earlier by Kaplin [4]. These models, especially the later ones, are based upon analyses by Pollock [2] of Viking lantler data. The models show that, even during severe dust storms with high optical depth, there is quite a bit of diffuse light present at the planetary surface. This availability of solar energy on the surface throws a new light upon the possible use of solar arrays for powering Mars survey landers and rovers.

The amount, of light available at any one place on the Mars surface varies from the following causes: changes in the Mars-Sun distance from orbital eccentricity, obliquity (axial tilt) of Mars to the orbital plane, solar zenith angle, and opt-ical depth. The changes in available light from orbital eccentricity, obliquity, and zenith angle are easily calculated [1,3]. However, t-he optical depth is not so easily modeled due to variable amounts of atmosphere c water and dust. Mars has light clouds and, near the north polar region, occasional fog. Since there is little water, the optical depth for fog and clouds on] y ranges from 0.01 to 0.2 and thus is not a serious problem. Dust, however, is a major concern.

'J'here are long periods when the atmosphere is relatively clear of dust- - an optical depth of 0.5 or less. When there is dust in the atmosphere, it changes with local, regional (long axis of affected area >2000 km), and occasional planet-encircling (one hemisphere) or global dust storms [3]. Local dust storms, which last on] y a few days and have an optical depth ranging from thin haze ($\tau<1$) through thick haze ($\tau>1$), occur each year. Local storms occur all over the planet but with higher probability near polar caps when the caps are evaporating. Global dust-s terms (estimated to reach an optical depth of 4 or more in southern latitudes with lower optical depths elsewhere) generally start in the southern tropical latitudes (0 to -30) during southern summer which occurs near perihelion.

Since the occurrence of dust storms at. any one location is based upon probabilities, it was decided to fully model the effects of optical depth on solar array operation. This model had to include the effects discussed above as well as intensity, temperature and spectral changes due to atmospheric dust.

COMPUTER MODEL

The computer model for available Mars surface solar irradiance will be presented in more detail in another paper [16]. The model has primarily been taken from equations presented by Applebaum and Landis [1] and Haberle, et-. al. [3]. In particular, there are two optical depth models presented in Ref. 1 which use different assumed starting points for the two 1977 global dust. storms. The first optical depth model assumes that the two dust storms seen by the Viking landers start-ed at latitude -30 degrees and areocentric longitudes 215 and 295 degrees respectively. The second optical depth model assumes that the first dust, storm started at latitude -30, longitude 215 and the second started at latitude -10, longitude 295.

Either of t-he above models can be selected in the program along with the capability to manually enter values for optical depth and surface albedo. When the opt. ical depth is manually entered the value for albedo is usually determined from a relationship [1]:

$$al = \max(al_T, \min(0, 18\tau, 0.4))$$

where al is albedo, τ is optical depth, and al_T is minimum albedo of **0.1**.

Using input values for areocentric longitude and lander latitude, the program first calculates or uses given optical depth and albedo values. Next, the program calculates the hourly zenith angle of the sun using 24 martian hours (a martian day, or SOl, is 24.65 earth hours). Tilt and orientation of the array or angle and attitude of a facet of an array are then taken into account- during t-he calculation of the angle of the sun to the array normal. The areocentric longitude is used to calculate the amount of light available above the atmosphere and Beer's law [1] is used to determine the direct beam light reaching the surface:

$$G_b = G_{ob} \exp[-\tau m(z)]$$

where G_b is direct beam irradiance on the surface of Mars, G_{ob} is the irradiance at the top of the Mars atmosphere, and τ is optical depth. The air mass function, m(z), is approximated by 1/cos z where z is t-he zenith angle.

The total global insolation reaching the surface is taken from analyses by Pollock, et. al. [2] and is calculated from a polynomial function of the optical depth, albedo and zenith angle [1].

The diffuse light is taken as the difference between the global and the direct beam values>. In cases of high optical depth, the direct beam value may be only a few percent of the total global value.

ARRAY CONSIDERATE ONS

Calculation of available solar array power starts with the designer selecting the latitude anti areocentric longitude, then array type, flat or faceted, then whether or not, there is shadowing and finally the type of cell, silicon or gallium arsenide. To calculate the array power output., a temperature calculation is made using the total global insolation value for heat input and an estimated value for convection cooling. The actual calculated temperatures fal. l within a range of a few degrees above zero to as low as -113 deg C. These values are comparable to martian surface temperature values since the martian surface absorptance and emissivity ratio is about- 1 - the same ratio as a silicon solar array. Calculation of array power uses separate algorithms for the direct beam, diffuse and albedo power contributions.

Corrections are made to the calculated power value to allow for the non-linearity of Voc and Isc due to low temperatures and intensities. A fifth order polynomial function [9] is used to make t-he temperature corrections.

A correction is also made which accounts for the spectral shift due to different levels of atmospheric dust. This correction uses t-he delta-Eddington approximation [14, 15] and makes use of light transmittance versus wavelength equations and data from Ref. 3 and solar AMO spectrum values from Ref. 8.

The product of the light transmitt.ante function and the AMO spectrum gives a spectrum which is increasingly red-shifted with increasing atmosphere c dust and zenith angle. Wavelengths around 800 nm are favored in the transmit-t.ante function. The red-shifted spectrum is then multiplied by the ratio of the total flux in the unmodified spectrum divided by the total flux in the modified spectrum. This rescaling cancels out any problems with intensity changes.

The rescaled, red-shifted AMO spectrum is then multiplied by the spectral response curve of the selected solar cell material to obtain t-he expected current output. A correction factor can then be obtained by comparing the integrated total current from the rescaled, red-shifted spectrum with the current. from the standard spectrum.

Results from the above computer model are presented in Figure 4 using as input-s the spacecraft baseline landing sit-e at -15 latitude and landing time of 195 areocentric longitude. Data is presented for optical depths of 0.5 and 4.0 with albedos of 0.1 and 0.4 respectively. The cell type was 10 Ω-cm silicon back surface field/reflector. Note the increase in correction due to diffuse lighting and consequent red-shifting of the spectrum.

DETAILED ARRAY DESIGN

The Voc and 1 sc temperature and intensity correct, ions al 1 ow a calculation of array series string operating conditions during a typical martian day. 1 n general , the string voltage can be expected to rise to about 25% above the value at standard conditions (AMO at 1 AU and 28 degC) in the early morning and I ate afternoon. The string VOI tage would be about, 4 % above the standard condition value at noon. Lower temperatures change resistances and fi 1.1 factor of the IV curve resulting in slightly revised efficiencies. Thus the array will produce less current at. higher voltages in the morning and afternoon and more current at lower voltages in the middle of the day. On days when there is a 1 ot of dust the amount of power produced will be more than originally expected due to a considerable amount of diffuse light which has a red-shifted spectrum.

'l'he foldout array for a lander with a nominal 28 V bus should have series strings with about 60 cells to give an operating peak power point of 30 V for standard conditions. This will result in a 31.8 V array in the middle of the martian da:y (near the equator) and a 37.5 V array in early morning and late afternoon. 'l'his large change in array operating conditions originally argued for a peak power tracker instead of a shunt regulator. Peak power trackers also can extract the maximum amount, of power from an array which is partially shadowed as at least one of the lander solar array petals will be. Shun L regulators have not, been ruled out since there is little available power at the extreme temperature and voltage conditions. It is possible tha L low intensity, low temperature (LILT) effects will be seen on Mars however there is little power loss expected since there is little power to be lost at these conditions.

CONCLUSIONS & FUTURE WORK

Preliminary analyses have shown that a solar array power system on the MESUR Pathfinder lander is feasible.

Use of high energy density, low cycle life (100+ cycles) secondary batteries is cost effective and provides insurance against uncertainties such as large dust storms.

No final decisions have been made at present on the effect- of dust deposition or erosion upon the array surface. There are indications in Refs. 3 and 10 that dus L is not, easily removed by wind once it has been deposited and Ref . 7 shows performance degradation. Erosion effects should be small since the lander arrays are horizontal [6] .

Chemical effects should also be small since normal array materials are resistant, [5] .

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The mat, erial from Reference 3 has not yet been printed and the authors are grateful for permission to use this material . Without the underlying science models developed over the years, this type of advanced technology application would not be

possible.

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CRUISE CONFIGURATION

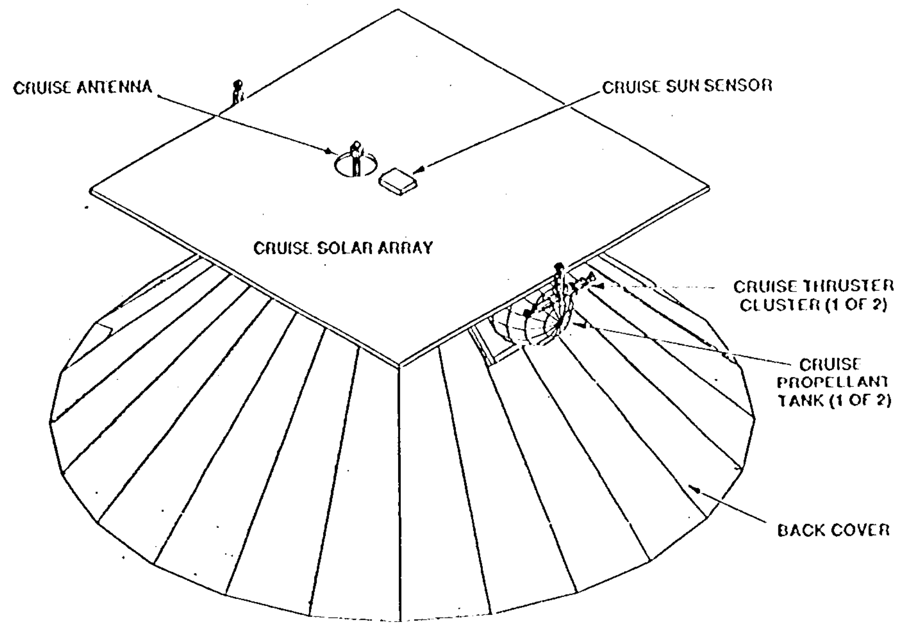

Figure 1

LANDED CONFIGURATION AFTER PETAL DEPLOYMENTS

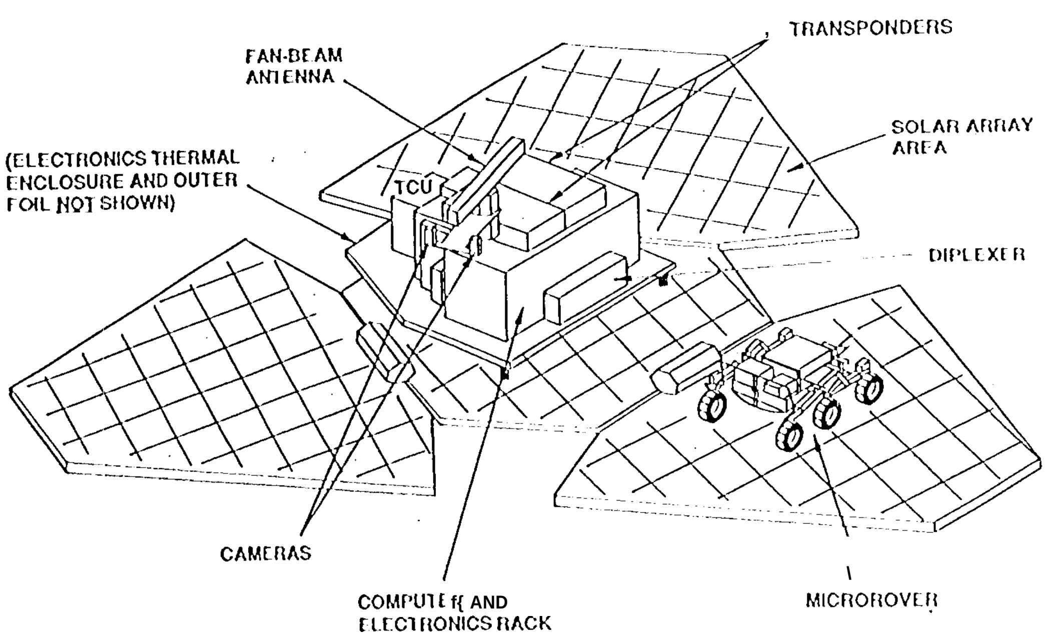

Figure 2

POWER SUBSYSTEM

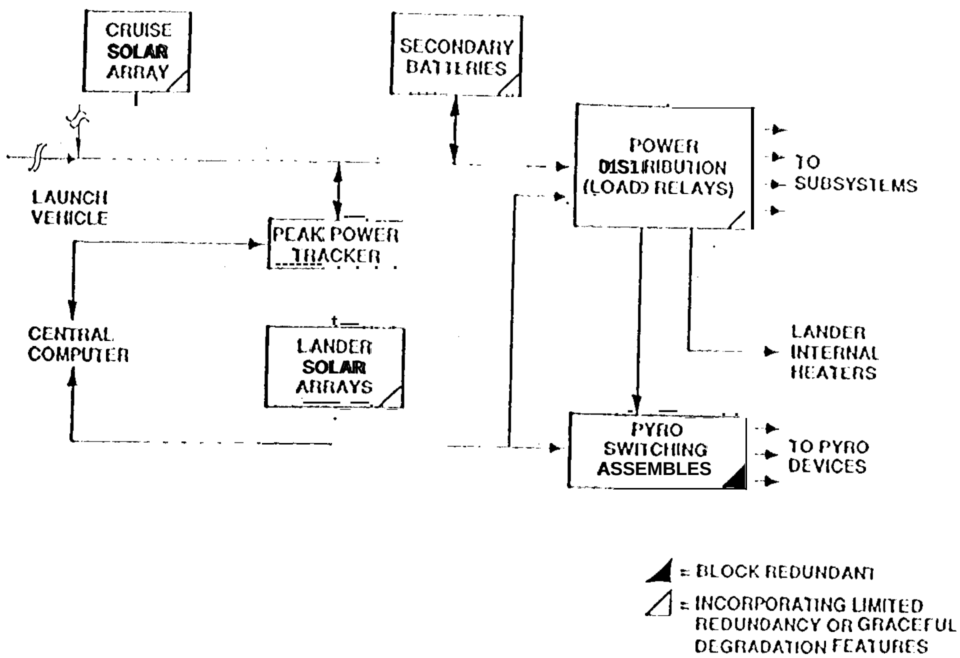

Figure 3

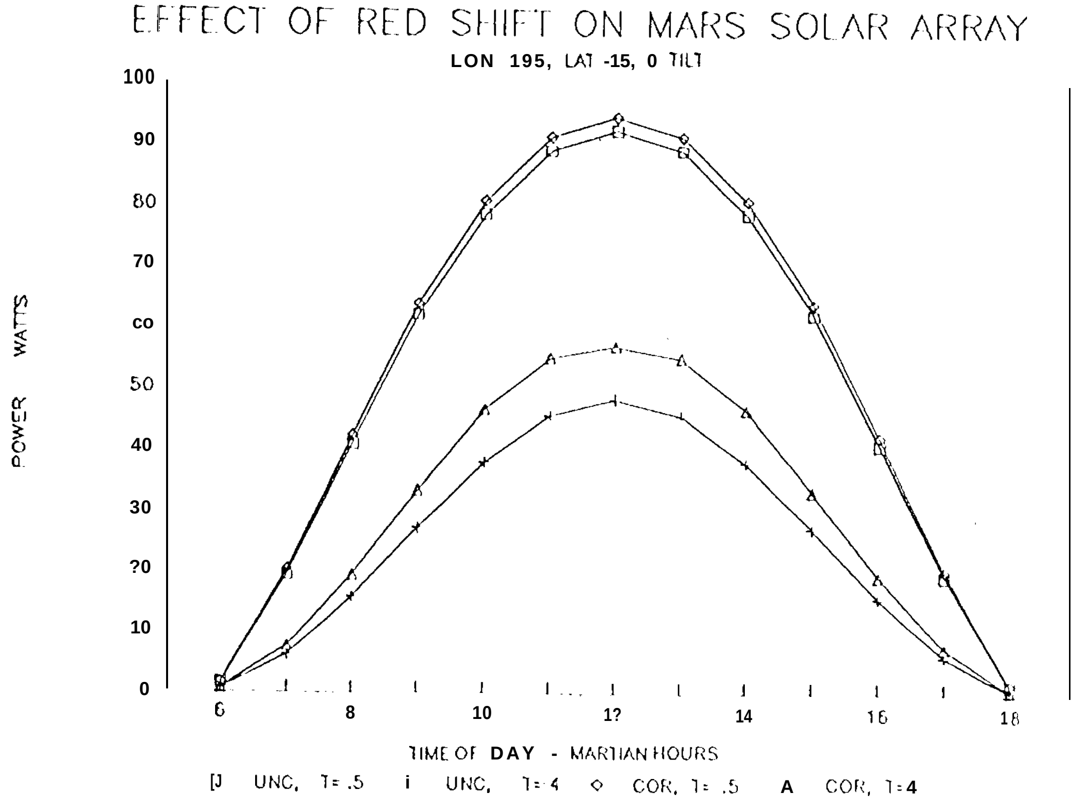

Figure 4